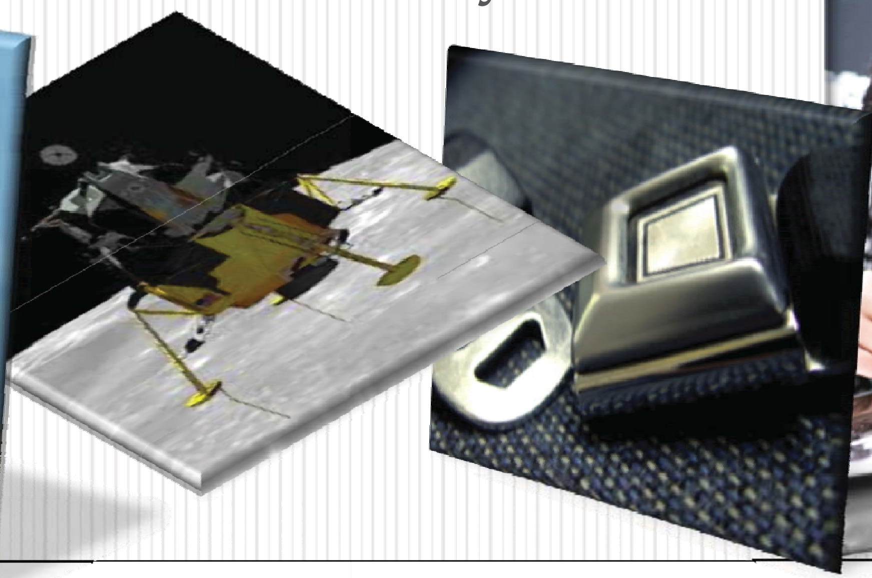
Economic Optimization of Innovation and Risk

AIAA Symposium | System Engineering

Robert Shuler | May 17, 2013



Goals of Presentation

- Introduce engineers to risk compensation
  - Generally engineers are not expected to read economics & psychology journals
  - Relation to other theories and existing practices
  - Striking and large examples of unexpected outcomes
- Present a quantitative equation for optimization
  - More appealing and useful to engineers than vague psych/econ theories
  - Quantitative rationale for reliability decisions, including some post-Columbia actio
  - Summary of derivation, details are in paper – http://mc1soft.com/papers
- Brief tutorial on applying the equation
  - Discuss a few of the examples in terms of equation parameters
  - Exercise: decision / alternatives on a hypothetical space project
    commercial passenger carrier for an orbital tourism / hotel facility

Background Theories

quant safety goals not
pted bec of uncertainty in
calculations
6 estimates of catastrophic
ure so high would threaten
litical viability of programs

- **Risk Analysis** *(Asipu 3200 BC, max release scenario for Nuc. Pwr. 1950s, probabilistic assessment post 1967 Apollo fir*
  http://www.rf...g/RFF/Documents/RFF-Resources-172_Risk_Assessment.pdf http://www.public.iastate.edu/~jdwolt/570X/2_RA%20History%20&%20Perspective.pdf http://www.econ-it2.eu/en/training/1-risk-management-1-1-the-...-the-origin-of-risk-analysis/
  - Engineering / Statistical hypothesis – combination of estimated probabilities *assumes a fixed mission profile (i.e. user behavior does not change – typically to an engine "human factors" means clarity and usability of controls, etc.)*

pre-2008 ratings of Mortgage-Backe
Securities & Credit Default Swaps

- **Risk Management** *(de Mere, Pascal, Fermat, Bernoulli, de Moivre, Bayes from 17th century, Markowitz 1952)*
  http://www.slideshare.net/ricardo.vargas/ricardo-vargas-historico-gerenciamento-riscos-ppt-en http://www.moaf.org/publications-collections/financial-history-magazine/93/_res/id=File1/Risk%20Management.pdf
  - Management hypothesis – identification, assessment & prioritization of risks *transfer, avoid, reduce or accept – assumes user behaves only as legally constrained*
  - Includes insurance, futures & derivatives, e.g. pre-sale of farm crops

NASA barred by law from using most
strategies – insurance, futures, deriv

- **Risk Compensation** *(Peltzman 1975)*
  - Economic hypothesis – humans & organizations optimize economic value *risk may partly adjust when an improvement is made*

Seatbelts do save
but not as many as

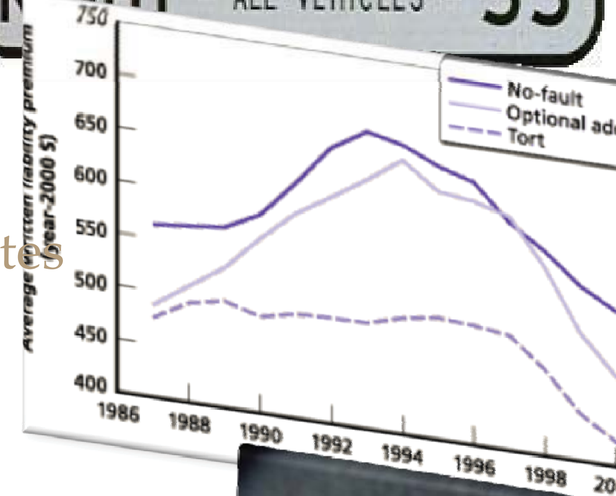
- **Risk Homeostasis** *(Wilde 1982)*
  - Psychological hypothesis – humans adjust behavior to maintain risk *improvement is wasteful*

e.g. More aggressive driv
with anti-lock brakes – a
condoms, bike helmets, skydivi

Unexpected Outcomes

TRAFFIC SAFETY

- Montana No-Speed-Limit 1995-1999
  - After 4 years, Montana recorded its historical low of number of accidents on affected roadways http://www.hwysafety.com/hwy_montana.htm
  - Since then accident rates have begun to rise again
  - German Autobahn accident rates are lower than USA rates

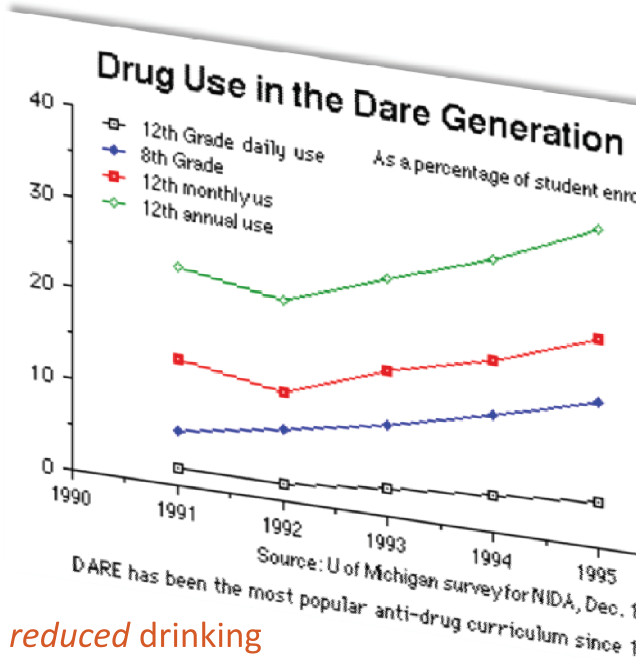


- No-Fault Auto Insurance
  - Leads to 6% increase in traffic fatalities
    Cohen & Dehijia, J. of Law & Economics 2004
- Seat Belts vs. Air Bags

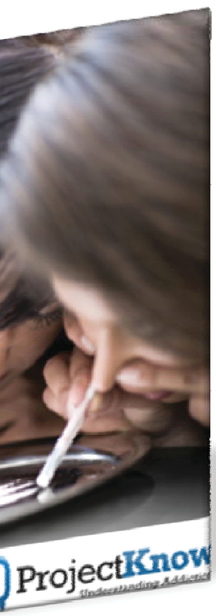
Levitt & Porter, Rev. of Econ. & Stat. 2001	**Cost per life saved:**
Seat Belts	$30k
Air Bags	$1.8M

Unexpected Outcomes

LARGE GOVERNMENT PROGRAMS



- War on Drugs – "Just Say No" – DARE
  - Pioneered in 1970s by Richard Evans at University of Houston
    - Nancy Regan phrase 1982
  - Testing by marketing experts shows:
    - "Just Say No" increased teen interest in drugs after exposure, promotes idea that other teens are using drugs – *usage has increased!*
    - DARE messages from police / authority not as effective as peer messages, e.g. publication of actual drinking statistics near dorms/frats on college campus *reduced* drinking
  - Costs:
    - Over $1 trillion & hundreds of thousands of lives
    - $33 billion for "Just Say No", $20 billion to fight in home countries, Columbia violence moved to Mexico, now directly affe border regions and tourism, $121 billion to arrest and $450 billion to incarcerate *non-violent* offenders



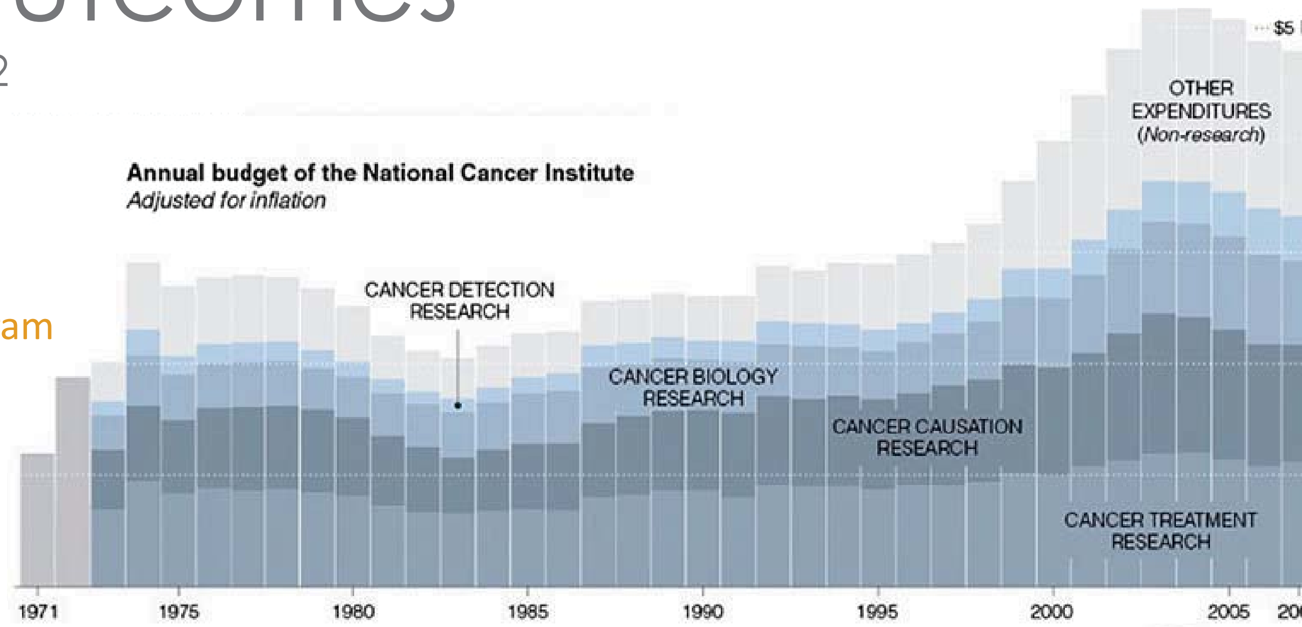
wiki/List_of_countries_by_incarceration_rate	per 100,000
1. USA	716
5. Rwanda	527
8. Russian Federation	502
92. United Kingdom	151
123. China	120

Behavioral, economic & possibly biologic factor

Unexpected Outcomes

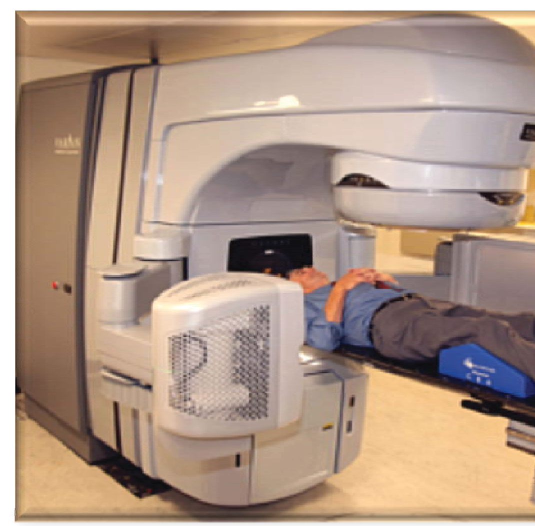
LARGE GOVERNMENT PROGRAMS #2

- War on Cancer
  - Begun by Nixon in 1971
    - Inspired by successful Moon program
    - Promised cure by 1976



Some economic factors may be involved – but clearly a technically difficult problem

NYT "Advances…" 4/23/2009	Change in death rate or incidence:
Cancer	-5% death rate (since 1970s)
Heart disease	-64% death rate (since 1970s)
Flu & Pneumonia	-58% death rate (since 1970s)
Smoking http://www.infoplease.com/ipa/A0762370.html	-54% incidence (since 1960s)
Illegal drug use http://www.umsl.edu/~keelr/180/trends.html	+6% incidence (since 2002)



Unexpected Outcomes

MISCELLANEOUS ACTIVITIES

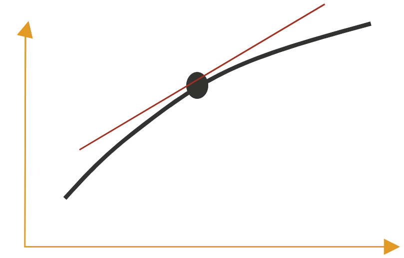
- Commercial Air Transportation
  - People will pay more for safety in the air – *Carlsson 2002*
  - Consumers learn about unobservable safety from flight outcomes – *Hartmann 2001*
    - Accidents adversely affect demand for other carriers
    - Airlines profits are greater if they are able to choose their optimal maintenance provision
    - Airlines AND consumers prefer an independent safety certification rather than an FAA minimum *makes it more profitable to provide additional maintenance*

- Fire Safety Blankets
  - For a long time mainly used in USA, *but USA has highest fire fighter death rate*
    - USDA Forest Service concern about entrapment risk with improved 2003 fire shelter, *developed with NASA he*
  - July 2005 British Columbia *bans use of fire shelters to prevent entrapment*
- Nuclear Energy

type of energy	*fatalities*	*% of world electricity*
Nuclear	5163 total	12.3% from 437 pla
Fossil fuels	300,000 per year	69.4%

Axioms & Approximations

- Use linear approximations
  - Equation will certainly be valid about an operating point:
  - May or may not work well for large deltas



- Cost of innovation axiom: *(equilibrium condition)*
  - Corporations will engage in ***innovation*** (adding **F**eatures, new models, etc.) until there no incremental **p**rofit $\mathbf{P_F}$ from doing so
  - Subsume all costs in P_F except **c**ost of the crash **r**ate C_R
  - $P_F - C_R = 0 \quad \Rightarrow \quad C_R = P_F$
  - Similar in concept to marginal utility of safety (Spence 1975, Savage 1999)
- Development Crash Rate approximation
  - Divide **d**evelopment cost C_{dev} by problem (bug) rate R_d to get cost per development bu C_d
  - To get total feature cost add **m**anufacturing $C_F \approx C_d R_d + M$
  - Rewrite: $R_d \approx (C_F - M)/C_d$

Agrees with our experience that hardware (M>0
has fewer bugs in development than software (C_d–

Axioms & Approximations

CONTINUED. . .

- Operational Crash Rate approximation
  - Use the concept of Defect ratio (defect leakage through testing process)
    - Not applicable to component wear/fatigue, but those processes are already well understood
    - Most modern failures are latent design or procedural issues:
      - All software failures, Fukushima reactor, Boeing 787 battery, Deepwater Horizon blowout, both Shuttle losses, etc.
      - Treat procedures like software, i.e. latent design issues (design of the procedure, or design of enforcement)
      - Even fatigue failures become latent design issues, i.e. they should have been caught by inspection / maintenance procedu
  - It follows that the operational failure rate is the development bug rate times D: $R_O \approx DR_d$ *(use consistent units – per hour, flight, device, etc.)*
  - Substituting for R_d we have $R_O \approx (C_F - M)D/C_d$ *or* $C_F \approx R_O C_d / D + M$
  - Gives a relationship between *operational failure rate R_O and cost of features C_F*
    - *Now we can apply our equilibrium condition – the cost of innovation axiom*

Note: our previous observations about development bug ra
now apply to operational failures ~
more expensive development process ⇒ lower the crash ra
more valuable features ⇒ more failures

The Crash Rate Model

- First, a ***profit axiom***
  - Economic utility (**V**alue) to users of the given **F**eature set: V_F
  - Seller/producer will set *price* = V_F to maximize profit: $P_F = V_F - C_F$
- Combine previous axioms & solve for crash rate:
  - Apply the innovation axiom to get cost of crash crashes (failures): $C_R = V_F - C_F$
  - Use operational crash rate axiom to replace C_F : $C_R = V_F - (R_O C_d / D + M)$
  - Solve for crash rate: $R_O \approx (V_F - M - C_R)D/C_d$
  - Express crash costs as cost per crash $C_C = C_R/R_O$
  - $\Rightarrow \quad R_O \approx \dfrac{V_F - M}{C_C + C_d / D}$

High value, easily produced features encourage more use and more risk taking $\Rightarrow$ high R_O

High *development costs* lower crash rate

Verification, inspection
analysis & quality c
multiply the effect
even if they are ch

n cost per failure (e.g. air
uclear) $\Rightarrow$ conservative &
careful use, low R_O

The Crash Rate Model

XPLAINS:

1. **How 6-sigma reliability helped Japanese automakers become largest in world (low "D")**
   - **- Now virtually all cars will go 200,000 miles**
   - **- After 20 years of competitive evolution, Japan has lost this advantage**
2. **How Boeing, ATT & IBM dominated with expensive but reliable products (high M & C_C)**
3. **Why you may not want to take a "fast-tracked" drug (C_d too low, D too high?)**
4. **Why your PC and phone crash a lot and are subject to hacker attacks (high V_F, low everything else)**

- First, a *profit axiom*
  - Economic utility (Value) to users of the given Feature set: V_F
  - Seller/producer will set price [illegible] V_F to maximize profit: $P_F = V_F - C_F$
- Combine previous axioms & solve for crash rate:
  - Apply the innovation axiom to get cost of crash crashes (failures): $C_R = V_F - C_F$
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The Bad News

$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$

- Competitive equilibrium
  - The formula assumes operation at the optimal profit point
    - If a company does not operate there, it will be acquired or bankrupted because *others have more money*
  - By culture, contracting, employee rotation & use of the same management consultants, *Government generally operates close to the same point as industry*
    - We have seen many administrations pledge to make "Government as efficient as industry"
- Data may be unavailable for D during development, V_F for gov't progr
  (i.e. profit)
- The Good News
  - It *may be* possible to shortcut 20+ years of trial and error and choose a "good" operating point – but we must learn how to react to new data

1979 Honda Civic

w.uniquecarsandparts.com.au/car_spotters_guide_japan_1979.htm

1979 Chevy Nova

http://www.detailshop.com/rides.php

Application to Examples

$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$

- Montana speed limit?
  - Perception of greater risk (high R_O) from
    - Bad crashes with speeding driver, high C_C
    - Greater risk of crash due to other driver's high D (errors)
  - Greater cognitive awareness of all risk factors vs. posted speeds which are consider by drivers to be conservative
- No-fault auto insurance?
  - Reduced C_C to driver, due to better insurance coverage and lack of fault penalties
- Seat belt and air bag effects?
  - Perceived slightly lower cost C_C (damage) from crashes when buckled
    - Relative to incorrectly perceived lower than actual risk/cost of unbuckled driving
  - Incorrect perception of near-immunity to CC with air bags, most crashes not head poor positioning of unbuckled occupants during crash
    - i.e. bags are of almost no value unless buckled up, and most of the protection comes from the belts

Application to Examples

$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$

- War on drugs?
  - Add supply-focused enforcement to cost of M
  - V_F made higher by erroneous “just say no” commercials
  - User C_C made lower by medical advances and free emergency room ruling
- War on cancer?
  - D ≈ 1 due to lack of a cure (all defects become operational defects)
  - Perceived V_F rises as hope for cure persuades people to undertake expensive treatr
- Air transportation?
  - C_C is high and perceived higher (lottery effect, disaster avoidance effect)
  - D is very low due to independent certification & investigation
  - Dependence of V_F on R_O, value of high risk airline or airplane drops to zero

Application to Examples

CONTINUED

$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$

We will analyze this
in the exercise – next

- Fire safety blankets?
  - Incorrect perception of low C_C of entrapment
- Nuclear energy?
  - Perceived extraordinarily high C_C of failure
  - Low D for same reasons as air transport
- Shuttle orbiter?
  - V_F is not directly measureable for non-profit space projects – perhaps use total cost
  - C_d and D are not known from easily accessible public records
    - Large testing costs applied to engines, avionics, tiles with many testing defects corrected high C_d/D
    - SRBs and foam were considered mature (low testing?) and many operational defects were ignored (high D)
  - Formula is meant to analyze a change (delta)
    - After 1986, military & commercial dropped – presumably V_F lower, change in R_O from 1/50 to 1/84 (nearly dou
    - In 1986 change from quasi-military crew to civilian (teacher) – no re-look at R_O – compare to WWII bombing r
    - Between planning and ops there was a 100 to 1 reduction in flight rate – how would this affect R_O ?

Project Manager Exercise:

$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$

- Commercial transport to orbital hotel / tourism facility
  - Goal is to sell tickets at V_F = \$1 million with recurring M < \$750k per passenger
    - Using next generation SpaceX reusable launcher 20x < cost of current \$133M for Dragon 7-passenger vehicle
    - 10 passenger reusable transport, dev cost \$250M, 2 copies
    - 1 flight a week gives 10 x 50 x 250k = \$250M/yr net revenue
    - Passengers sign waiver of liability but this is not expected to hold up in case of vehicle systems failure
    - At-fault accident liability estimated at \$1B and no one will insure at reasonable price
  - Hotel & investors insist R_O << 1 / 5 years to guarantee profits after liability
    - 1 / 25 years would be 1 / 1250 flights, still 1000x more risky than a 1000 mile auto trip (1 fatal crash / 100M m
  - Testing program
    - 10 test flights, revealing 5 major but not fatal problems, giving C_d = \$50M
    - You are confident from risk analysis and test results that D < .1 (one more problem in another 10 flights)

$$R_O \approx \frac{\$1M - .75}{\$1B + \$50M / .1} = \frac{.25M}{1.5B} = \frac{1}{6000}$$

seems like a pr
good number

Crisis:

$$R_O \approx \frac{\$1M - .75}{\$1B + \$50M / .1} = \frac{.25M}{1.5B} = \frac{1}{6000}$$

$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$

- After R_O publication & failure of a competing spacecraft:
  - Oops, that's only 600 flights, with a crash expected every 12 years
  - Ticket sales top out at 100 due to perceived risk, the venture will fail
  - Hedge fund offers to rescue company, alter ticket price to $5M
    - 10 flights / year, revenue of $500M, mostly profit
  - Founder asks you…
    - What is risk of hedge fund plan?
    - How much money do you need to meet original goal of 25 year crash interval expectancy?

$$R_O \approx \frac{\$5M - .75}{\$1B + \$50M / .1} = \frac{4.25M}{1.5B} = \frac{1}{353}$$

Due to low flight rate and high financial pressure on each flight n plan expects crashes every 3.5 yea

$$R_O \approx \frac{\$.95M - .75}{\$1B + \$70M / .05} = \frac{.2M}{2.4B} = \frac{1}{12000}$$

Spend another $100M for 10 test fl (total 20) and if no problems, D < . & reduce ticket price $50k

S/W Air, one of the lowest ticket price carriers, is also one of the safest

Caveats:

$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$

- Linear approximation range may be violated in this example
  - Still extremely useful for detecting *direction* of change and *incremental amount of change*
- Static equilibrium equation only
  - Does not consider dynamics (speed), but humans respond remarkably fast, consider aviation inferences
  - All eggs in one basket equation, portfolio (Markowitz) approach unused by NASA since early 80s
- Determination of D is not statistically valid
  - Infeasible to mount thousands of large missions
  - Use engineering analysis & inference methods along with independent verification [next slide]

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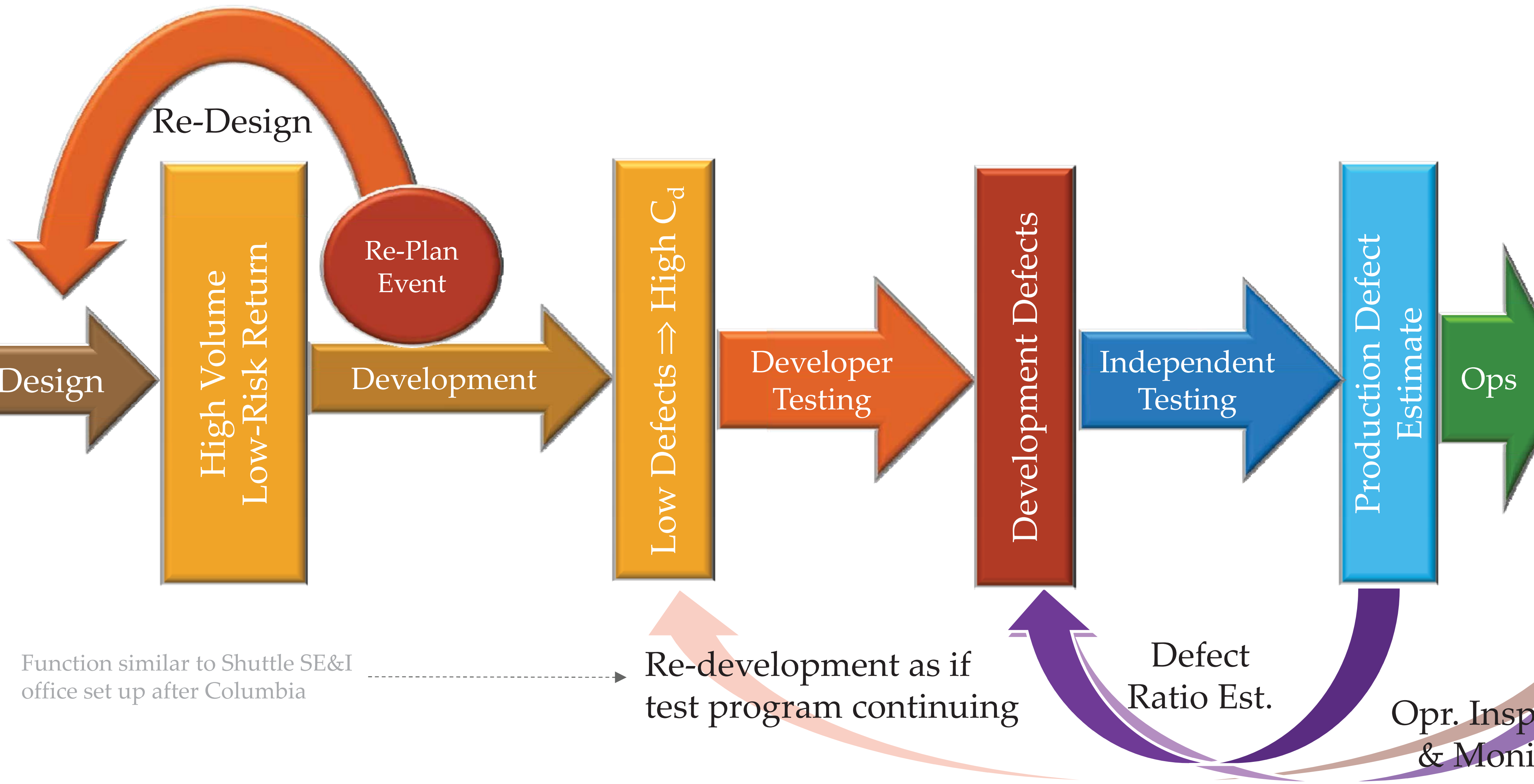
A Methodology Suggestion

HOW TO APPLY "SMARTS" EFFECTIVELY

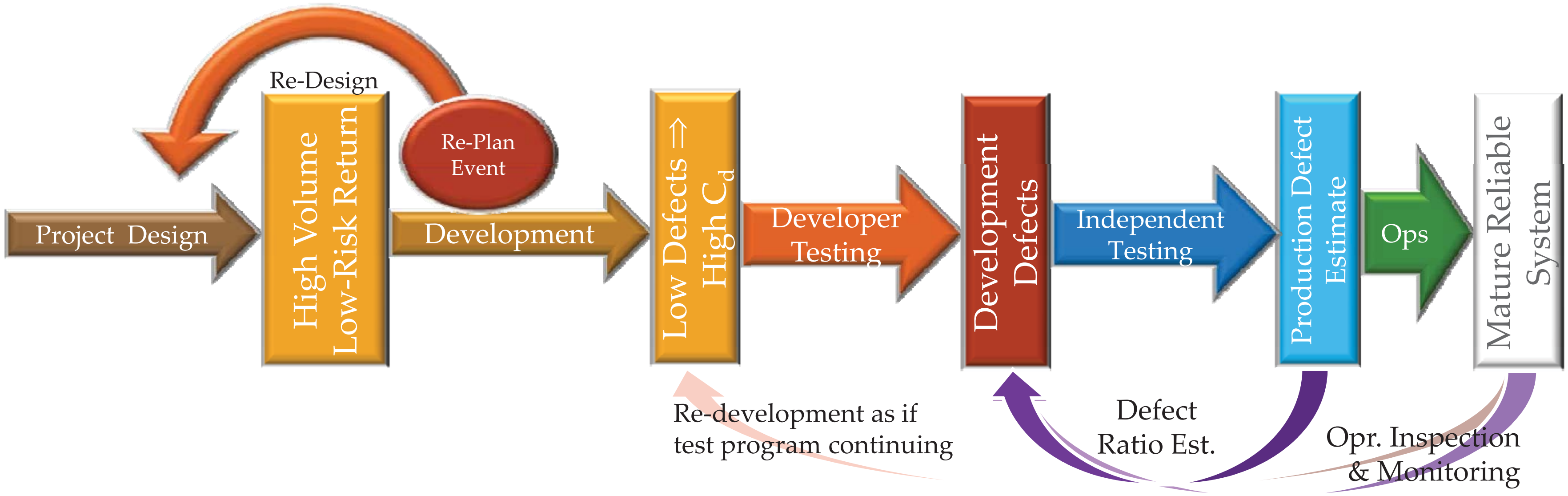
$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$



Conclusions:

$$R_O \approx \frac{V_F - M}{C_C + C_d /}$$

- Provides insight into effects such as mission frequency and testing
  - Economic theory (supply curve, more is more difficult) is at odds with Engineering experience (learning curve)
- Needed to provide rapid adaptation to new technology
  - 20 years is too long to "gain experience" with current & proposed rates of introduction of new technologies
- Cheap vehicles need many test flights to lower D
  - Expensive verification is incompatible with the concept "cheap" – relying on C_C restricts value of missions V_F
  - Alternative (used in the exercise) is to get D very low, taking advantage of the low cost of missions for verificat
  - Need a way to account for distribution of severity of defects (often logarithmic, e.g. earthquakes, foam loss?)



Summary of Engineering Effects

crash rate

$$R_O \approx \frac{V_F - M}{C_C + C_d / D}$$

creative design

industrial engineering, automation & labor management

system engineering and project management

safety engineering

social engineering

process efficiency

test and verification